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ORIGINAL ARTICLE

Influence of Multiwall Carbon Nanotube on Mechanical and Wear Properties of Copper – Iron Composite

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ABSTRACT – Multiwall carbon nanotubes (MWCNTs) are attractive due to their novel physical and chemical characteristics, as well as their larger aspect ratio and higher conductivity. Therefore, MWCNTs can allow tremendous possibilities for the improvement of the necessarily unique composite materials system. The present work deals with fabrication of Cu-Fe/CNTs hybrid composites by powder metallurgy techniques. Copper powder with 10 vol.% of iron powder and different volume fractions of Multi-Wall Carbon Nanotubes (MWCNTs) were mixed to produce hybrid composites. The hybrid composites were fabricated by adding 0.3, 0.6, 0.9, and 1.2 vol.% of MWCNTs to Cu- 10% Fe mixture using a mechanical mixer. The samples were compressed under a load of 700 MPa using a hydraulic press to compact the samples. Sintering was done at 900°C for 2 h at 5ºC/min heating rate. The microscopic structure was studied using scanning electron microscope (SEM). The effect of CNTs on the mechanical and wear properties, such as micro-hardness, dry sliding wear, density, and porosity were studied in detail. The wear tests were carried out at a fixed time of 20 minutes while the applied loads were varied (5, 10, 15, and 20 N). SEM images revealed that CNTs were uniformly distributed with relative agglomeration within the Cu/Fe matrix. The results showed that the hardness, density, and wear rates decreased while the percentage of porosity increased with increasing the CNT volume fraction. Furthermore, the wear rate for all the CNTs contents increased with the applied load.

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INTRODUCTION

Metal matrix composite is a relevant material used in achieving many industrial requirements and automotive applications. Copper is considered one of the essential materials used to manufacture composite materials because it has excellent properties such as corrosion resistance, conductivity (thermal and electrical), as well as a relatively high melting point [1–4].

Powder metallurgy technique (PMT) is an incorporated process for developing state-of-composite materials. PMT begins with a homogenous mixing of the matrix powder with reinforcement, followed by compaction at a suitable pressure, then, sintering of the compacted specimens at chosen environments for components densification. Nevertheless, by utilising the traditional PMT, the interfacial bonding of reinforcements and matrix shows to be limited due to their respective insolubility, which results in high porosity content, low density, and reinforcement's separation [5–8].

Increasing demand for materials with exceptional properties in recent years, the use of carbon nanotube (CNT) has become necessary to achieve this purpose. Carbon nanotubes have been expected as the perfect material to increase the properties of solid materials owing to their strength, high elastic modulus, and aspect ratio. Several types of research have shown that incorporating CNTs into metals, ceramics, and polymers can dramatically enhance their mechanical properties [9–13]. Multi-walled carbon nanotubes are one of the best materials that can be used as reinforcement materials due to its excellent properties [10, 14]. Some difficulties include the interface resistance (i.e. mechanical, thermal) between the CNTs and the metal-matrix, in addition to CNTs distribution in the matrix. Despite that, the properties of the composite increase by using CNTs compared to the pure metallic matrix [15, 16]. Hybridisation is a process of combining two or more types of reinforcement to produce a material with high mechanical specifications [11, 17]. The superior mechanical and thermal properties of Cu-CNT composites make it the most successful among metal-CNT composites. Therefore, many kinds of research have been implemented to manufacture this composite and improve its properties by modifying the factors that influence on the composite characteristics [18]. CNT tends to agglomerate due to its broad specific surface area and influence of Van der Waals forces. CNT clusters degrade the desired properties of the composite because it behaves as discontinuities, and that increases the porosity. Also, the non-uniform dispersion of CNT and clustering produced inhomogeneous property distribution. Therefore, the mixing process must be done well to ensure homogeneous distribution of particles [19]. Koti et al. [20] used powder metallurgy techniques to prepare Cu-CNT composites and found an increase in the microhardness with increasing CNT content up to 0.75 wt.%. Mallikarjuna et al. [21] studied the mechanical properties of CNT-SiC/Cu hybrid nanocomposite fabricated by powder metallurgy techniques. They found that with increasing CNT content, the grain size of the composite decreases and the hardness improves when compared

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with copper. Xu and Li [22] prepared CNT/Cu composites by powder metallurgy techniques and found that CNT/Cu composite exhibited lower wear rates compared to unreinforced copper at similar conditions.

Many researchers have investigated the wear and mechanical characteristics of copper matrix composite reinforced with CNTs; however, the wear and mechanical characteristics of hybrid Cu–Fe–CNTs composites produced through PMT are yet to be investigated. Therefore, the objective of this study is to evaluate the effects of CNTs concentration on the wear and mechanical characteristics of copper-iron composite synthesised via PMT.

EXPERIMENTAL SETUP

Composite Preparation

Elemental copper powder (99.8% purity, ≤ 25 μm average particle size (APS)), iron powder (99.9% purity, 10 μm APS), and MWCNT (purity = > 95 %, average diameter = 8-15 nm, length = 10-50 μm) were used in the study. The copper powder was mixed with 10 vol.% of iron powder as a constant volume fraction with varying amounts (0, 0.3, 0.6, 0.9 and 1.2 vol.%) of MWCNT. The mixture of Cu – Fe – MWCNTs was produced by mixing the powders in a Turbula mixer for 15 min. The mixture of the powders was cold-compacted using the "universal testing machine" (HOYTOM) with a uniaxial pressure of 700 MPa for one minute to produce cylindrical samples (D: 10 mm and H: 6 mm). The pressed samples were sintered using cast iron and graphite powders (to prevent the oxidation) at 900°C for 2 h at 5ºC/min heating rate and then left to cool naturally inside the furnace after the power was turned off. Figure 1 showed the samples after the sintering process with various volume fractions of CNTs.

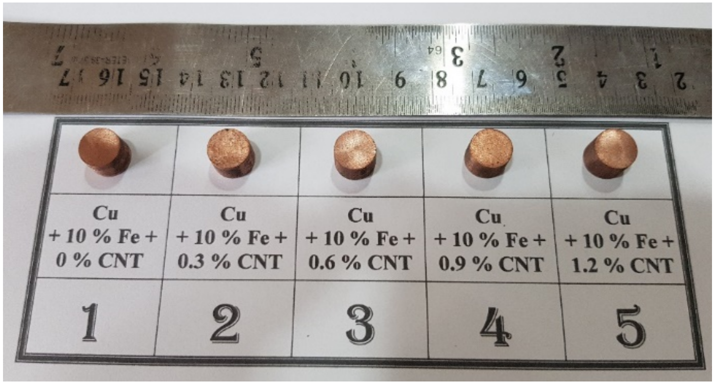


Figure 1. The study samples according to the reinforcement ratios.

Characterisation and Testing

The Archimedes principle was applied in the determination of experimental density and porosity of the samples according to ASTM B962-8 [23, 24]. Rule of mixtures was used to determine the theoretical density of the hybrid composites; the determined densities of Cu, Fe, and MWCNTs used were 8.940 g/cm^3, 7.870 g/cm^3, and 2.10 g/cm^3, respectively [25]. The experimental and theoretical densities, as well as the porosity (P) of the samples, were measured using Eq. (1), (2) and (3) [26–28].

$$\mathrm{ED} = \frac{\mathrm{M_a}}{\mathrm{M_a} - \mathrm{M_i}} \times \mathrm{D_w} \tag{1}$$

where ED, Ma, Mi, and Dw are the experimental density, the samples' dry weight, sample weight when suspended in distilled water, and density of water, respectively.

$$\mathrm{TD} = \sum (\mathrm{TD_i} \times \mathrm{X_i}) \tag{2}$$

where TD, TDi, and Xi are the theoretical density, the theoretical density of the individual composite elements, and the volume fraction of the individual elements present in the composite, respectively.

$$\mathrm{P} = \left[1 - \left(\frac{\mathrm{ED}}{\mathrm{TD}}\right)\right] \times 100\ \% \tag{3}$$

SiC emery sheets of various grades (600, 1000, 1500) were used to grind the samples, followed by polishing using aqueous alumina with a particle size of 1 μm suspended in water. Scanning electron microscope (Model: Viga-3, Belgium) was used to obtain the scanning electron micrographs of the samples. According to ASTM E384-08 [29], Micro-Vickers hardness tester (Model: HVS-1000, USA) was used to get a samples' microhardness value with a load of 490 g and holding time of 20 sec. Five readings were taken for each sample by carefully picking a region that includes both the reinforcement and the matrix. "A pin-on-disc wear testing machine" (Model: ED-201, Disc material: Steel, Hardness: 62

HRC, India) was used to perform the dry wear test according to ASTM G99 [30]. The hardened steel disc was rotated against the sample while the pin was kept stationary. The wear track diameter and disc rotation speed were 60 mm and 480 rpm, respectively. All the samples were tested at a constant sliding time of 20 min and various applied loads of 5, 10, 15 and 20 Newton. Before and after each wear test, the samples were weighted to expedite the calculation of the wear rate. Acetone was used for cleaning the cylindrical pins and the hardened steel disc prior to each test. Four specimens were utilized for all the tests specified above and the average value for each test was calculated.

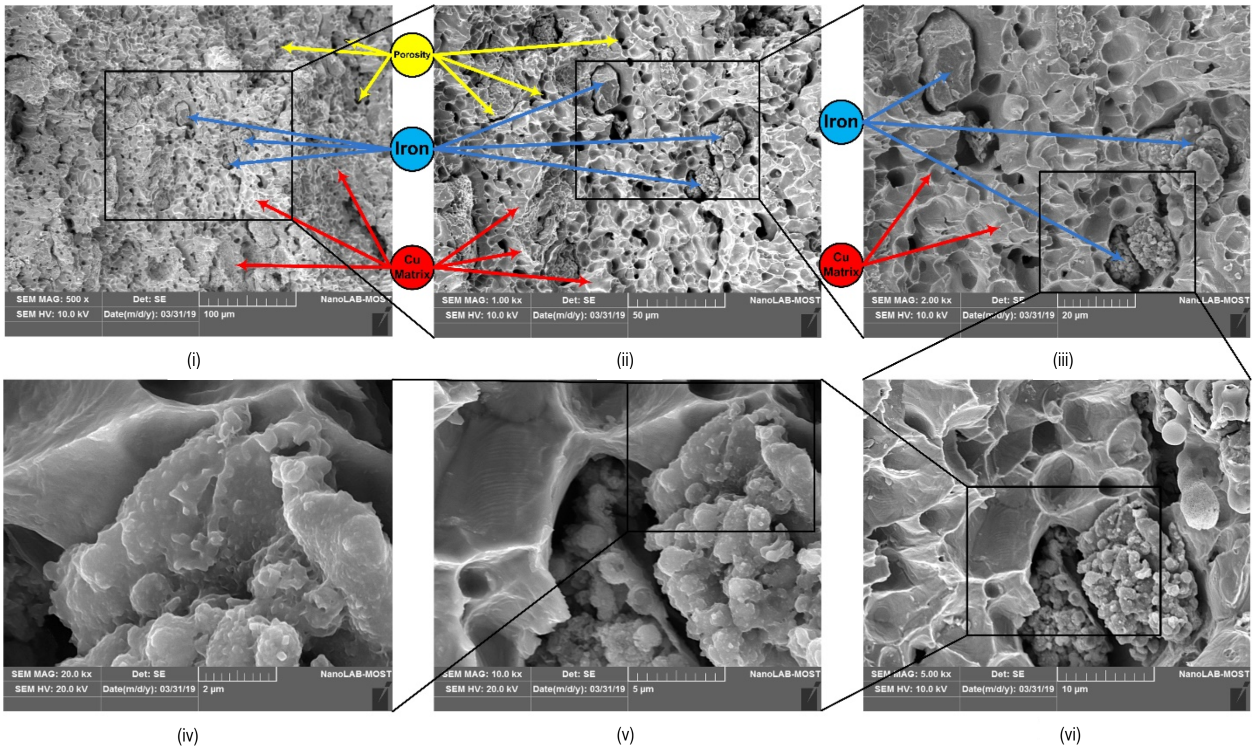
RESULT AND DISCUSSION

Microstructure Analysis

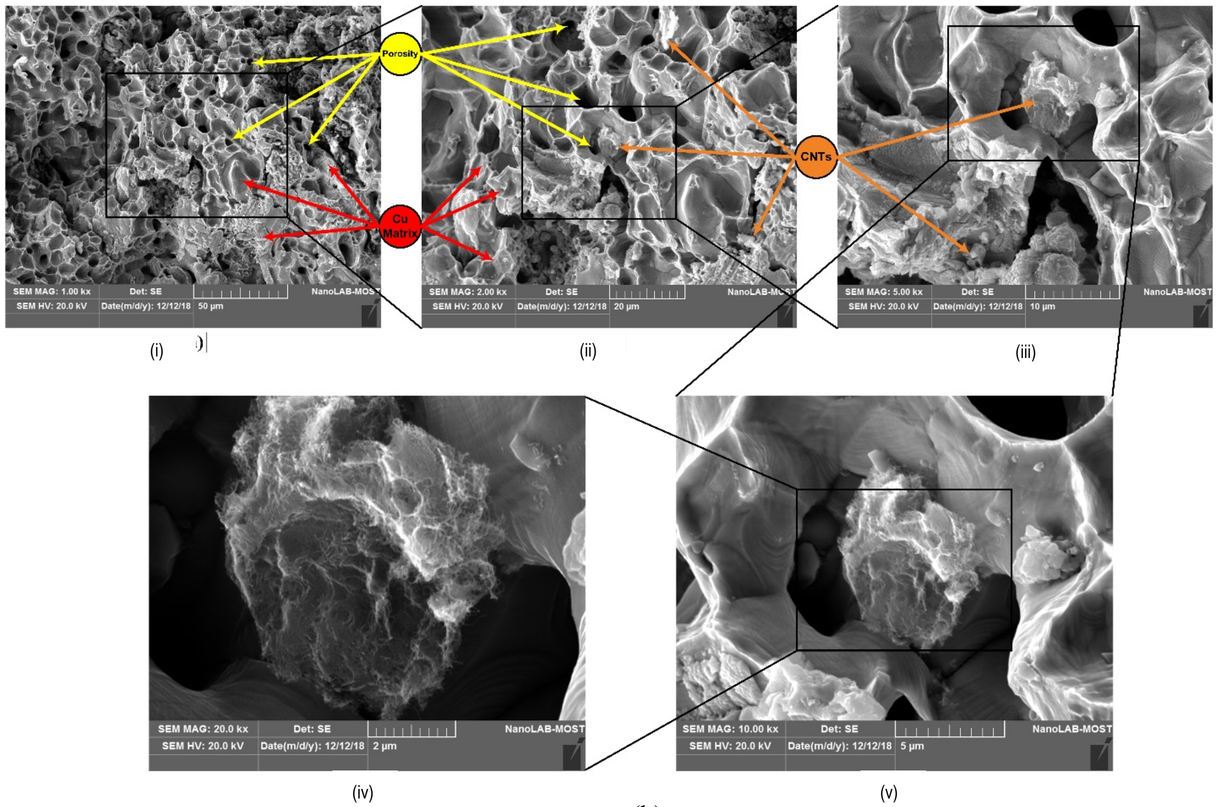
The SEM images of the composite without CNTs and hybrid composites with 0.6 and 1.2 vol.% of CNTs are shown in Figure 2. These images showed well-bonded copper particles due to the compacting and sintering process. Also, the images showed homogenous CNTs distribution in the metal matrix with a partial clustering and agglomeration in high CNTs content due to interlocking between CNTs themselves. The SEM micrographs showed some voids in the composites; these voids were increased with increasing CNTs content, and this agreed with the measured porosity in these composites. The SEM images showed that the powder particles of both metals diffused into each other, and into the created pores at the grain boundaries. The incomplete diffusion process and grain growth were the cause of these pores [19].

Density and Porosity Measurements

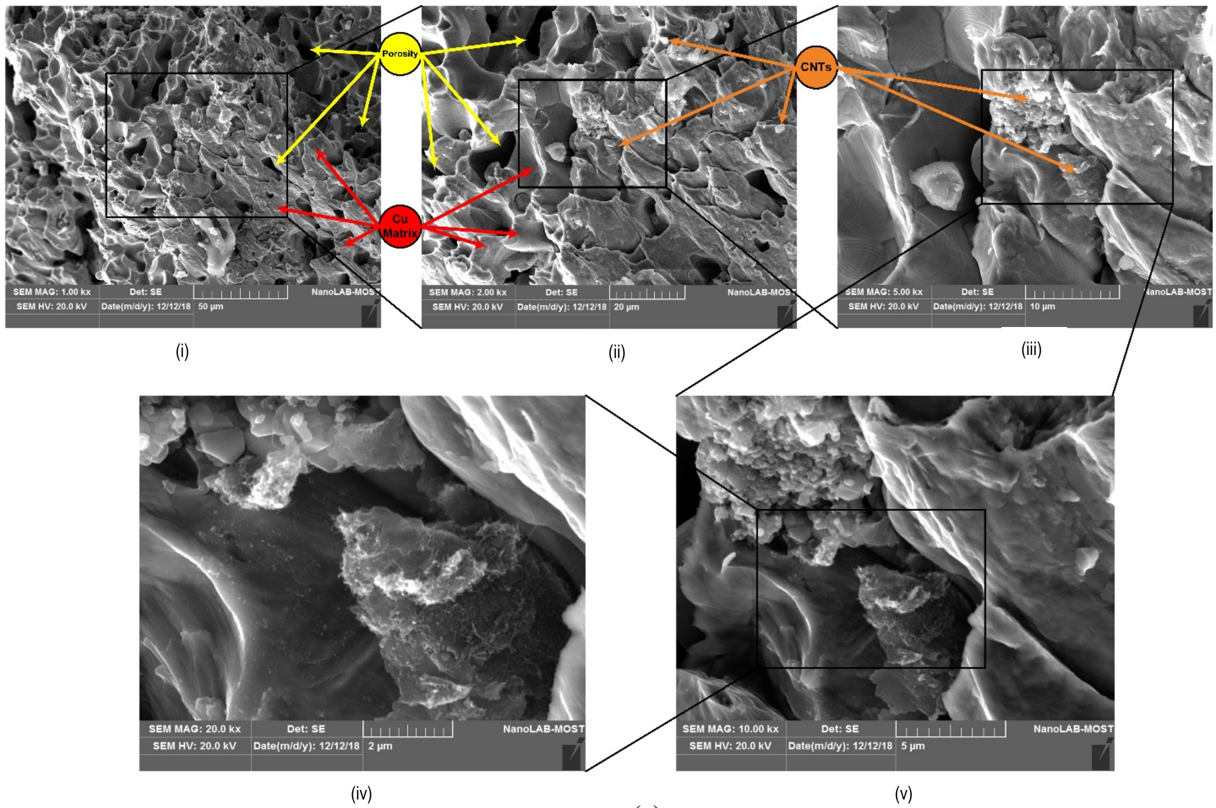
The relationship between the concentration of CNTs and different porosities and densities of the hybrid composite was shown in Figure 3. Observably, the hybrid composites showed decreased experimental density with an increasing amount of CNTs when compared to that of theoretical density. This decline of density was due to the lower value of the density of CNTs in comparison with powders of copper and iron in addition to the increased percentage of porosity and agglomeration of CNTs as the nano-powder content increases as shown in the SEM micrographs (Figure 2) [20]. The porosity was increased when the concentration of was CNT increased due to the agglomeration of the nano-filler. The considerable surface energy of CNT resulted in strong interactions between its particles, and that effectively reduced the distribution process. This behavior agreed with the results of Liew et al. [31].



(a)



(b)



(c)

Figure 2. SEM views of (a) Cu/Fe - 0% CNTs, (b) Cu/Fe - 0.6 % CNTs, (c) Cu/Fe - 1.2 % CNTs.

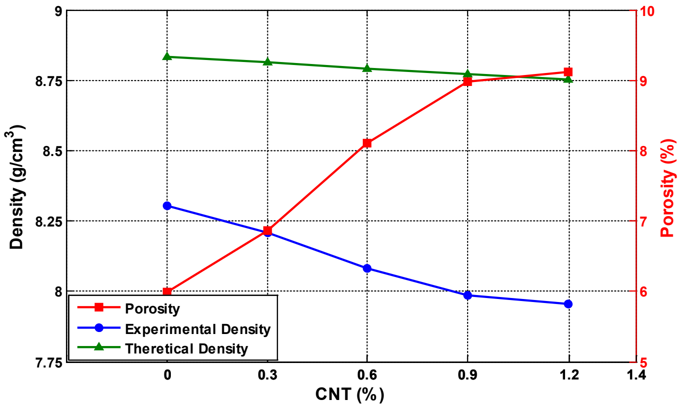


Figure 3. Variation of measured density and porosity with CNT content.

Microhardness

For any material, the hardness is a function of the microstructure and the type, size, shape of its reinforcements. Figure 4 showed the influence of CNTs on the microhardness characteristics of the hybrid composites. Observably, the hardness showed a decreasing trend with increasing CNTs content in the copper matrix due to the lower densification and higher agglomeration of CNTs within the matrix. These agglomerates increased the percentage of porosity and reduced the hardness instead of reinforcing it [21].

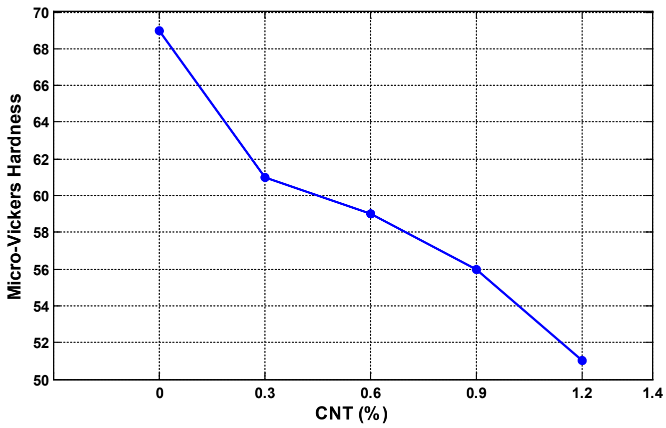


Figure 4. Variation of microhardness with CNT content.

Wear Rate of Composites

Effect of CNTs Content on Wear Rate

The relationship of the CNTs volume fraction with the wear rate at different applied loads was represented in Figure 5. The hybrid composites that contained different percentages of CNTs had the minimum wear rate compared to the Cu-Fe composite. This decline in wear rate values showed an increasing trend as the CNTs content approaches the minimum value at 1.2 % CNTs. This observed improvement could be due to the high lubrication attribute of CNTs, in addition to the uniform distribution of CNTs within the matrix. The debris between two surfaces gradually spread out, forming a layer of lubricating film, and that minimized the further removal of the material [22]. The uniform distribution of the nanotubes within the copper matrix further prevented the peeling of copper grains near the work surface.

Load Effects on Wear Rate

Figure 6 shows the wear rate of hybrid composites under the same test conditions. Evidently, the wear rates showed an increasing trend with the load at varying CNTs volume fractions in obedience to the Archard's law [32, 33] which provides that wear rate is directly proportional to the normal load [34]. Because the friction and contact between the two surfaces increased, there was a rapid deformation of the hybrid composites as a result of compressive and frictional forces that dominated in dry sliding.

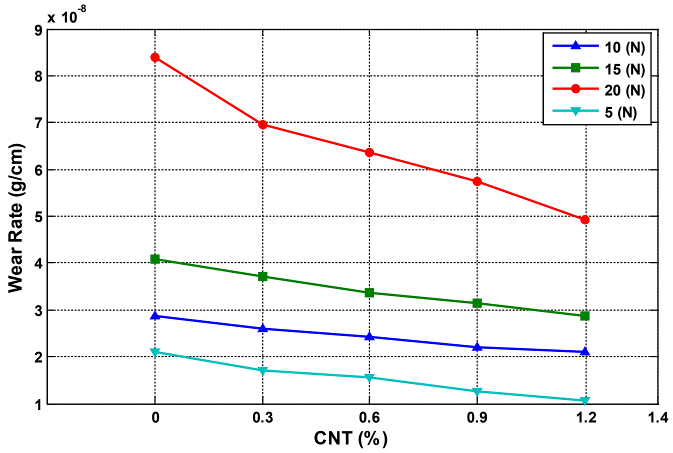


Figure 5. Variation of wear rates of the hybrid composites with the different volume fraction of CNTs.

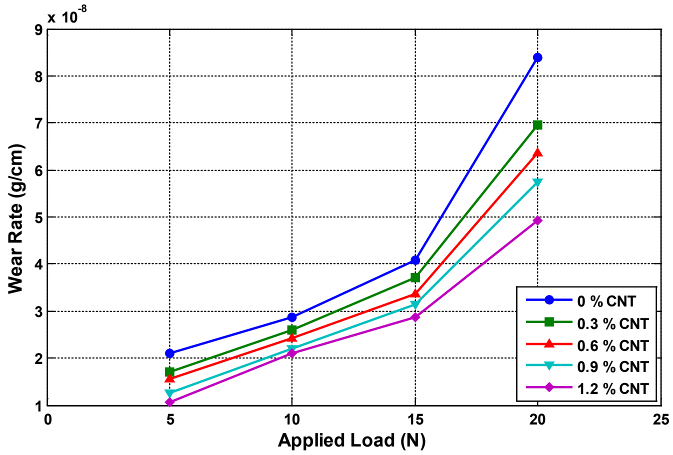


Figure 6. Variation of wear rates of the hybrid composites with varying applied loads.

CONCLUSION

The powder metallurgy technique was used in this study to successfully reinforce copper-iron matrix composite with the various MWCNTs volume fractions. From the observations, it is concluded as follows:

i. The density and microhardness values of composites decreased with increasing volume fraction of CNTs until up to 1.2 vol. %, while the percentage of porosity increased when compared with pure copper.
ii. The wear rates significantly decreased during the sliding wear process by retarding the peeling of copper grains by iron particles and CNTs.
iii. The wear rate related directly to the applied loads.
iv. The most critical issue that influences the mechanical characteristics of metal-CNTs composites is the manner of CNTs distribution in the metal matrix.

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